# NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3011

## COEFFICIENT OF FRICTION AND DAMAGE TO CONTACT AREA DURING THE EARLY STAGES OF FRETTING

## I - GLASS, COPPER, OR STEEL AGAINST COPPER

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Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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## SUMMARY

Experiments were conducted to measure the coefficient of friction $\mu$ and to determine the damage to the contact area during early stages of fretting of copper at a frequency of 5 cycles per minute. Specimen combinations of copper against glass, copper against copper, and copper against steel, as well as various copper oxide films and powder compacts, were used.

The results lead to the conclusion that fretting of copper starts with the same mechanical damage that occurs during unidirectional sliding. Fretting of copper against glass, copper against copper, and copper against steel starts with adhesion and metal transfer (galling) with accompanying high $\mu$ values ($>$ 1.0) the same as those obtained during unidirectional sliding. After the initial high values of $\mu$, a reduction in $\mu$ was observed, associated with reduced plowing and an increasing concentration of debris in and around the contact area. After approximately 100 cycles of fretting, $\mu$ reached a constant value (0.5-0.6) approximately the same as that obtained with compacts of either cuprous or cupric oxide.

The presence of preformed cuprous or cupric oxide films on copper does not delay the occurrence of fretting but only lowers the initial coefficient of friction.

## INTRODUCTION

Fretting, defined as surface damage that occurs when contacting solids experience slight reciprocating slip, creates problems in machines subject to vibration. The wear, pitting, and debris caused by fretting of some metal surfaces, particularly in aircraft, causes loss of tolerance, increased fatigue susceptibility, and seizure.

The prevention or inhibition of fretting is dependent upon an understanding of the basic mechanism, which has not been definitely established.

In recent unpublished research by H. H. Uhlig, it was theorized that fretting is caused by the scraping off of regenerative oxide films and some underlying base metal. Other investigations (refs. 1 and 2) have indicated that fretting is caused by adhesion and cold-welding or interlocking, formation of loose metal particles, and subsequent oxidation of the particles. Evidently, more detailed information is needed, particularly on the start of fretting, inasmuch as an understanding of the start is important in considering means of prevention. The initial stages (0 to 500 cycles) of fretting were investigated at the NACA Lewis laboratory by measuring coefficient of friction $\mu$ and observing damage. The results were compared with data obtained during unidirectional sliding under similar conditions and with data from other investigators. 2929

Fretting was produced by reciprocating a flat specimen in contact with a convex specimen at a frequency of 5 cycles per minute, an amplitude of 0.006 inch, and a load of 175 grams. A continuous record of the coefficient of friction was made. The measurements and observations were limited in most cases to 300 cycles. Copper against glass, copper against copper, and copper against steel, as well as other combinations using cuprous and cupric oxide films and powder compacts, were employed. Copper was also fretted against copper in the presence of hexadecane to determine the effect of reduced oxygen availability.

## APPARATUS

The apparatus (fig. 1) was designed to produce fretting at low frequency so that friction force could be measured and close observation made of the start of the fretting action. A flat specimen slid back and forth in contact with a convex specimen under a normal load of approximately 175 grams, applied by setting weights on the flat specimen. The flat specimen was held horizontally by a clamp attached to a beryllium-copper dynamometer ring (1.5 in. diam, 0.5 in. wide, and 1/64 in. thick). The linear reciprocating motion of the dynamometer ring and flat specimen holder assembly was achieved by a nut traveling on a screw oscillated by a synchronous reversible motor. The velocity of 0.156 inch per minute of the nut was obtained by using a 10-rpm motor having a screw of 64 threads per inch.

The amplitude of 0.006 inch was controlled by a pair of adjustable limit switches, actuating a relay which reverses the motor. This combination of amplitude, sliding speed, and general dynamics of the apparatus gave a frequency of about 5 cycles per minute. For unidirectional sliding experiments (under conditions identical to those of the fretting runs), the amplitude was set at a large value by proper adjustment of the limit switches.

The friction force was measured by a strain gage attached to the dynamometer ring. As the nut pushed and pulled, the ring and the strain gage were alternately compressed and stretched, in proportion to the sliding resistance or friction force between the flat and convex specimens. A corresponding fluctuating direct-current voltage was obtained across the strain gage and the signal was amplified and recorded on paper by a photoelectric potentiometer. The apparatus was calibrated by applying known forces to the dynamometer ring and noting corresponding deflections on the potentiometer. Thus a record of friction force (hence coefficient of kinetic friction) was obtained as fretting progressed. Maximum experimental error was estimated to be $\pm 5$ percent.



Most of the experiments were conducted in air of relative humidity between 5 and 10 percent. This condition was achieved by enclosing the whole apparatus in a Lucite box, and maintaining a flow of clean dry air through the box during the entire fretting run. The air was cleaned and dried by passing through glass wool, activated alumina, and calcium chloride.



Microscopic observation was made of fretting action occurring between glass and copper. In this case the top of the Lucite box was made of rubberized cloth having a hole for the microscope objective.

## MATERIALS AND PROCEDURE

Materials. - Electrolytic copper was chosen as the basic specimen material because of its purity, homogeneity, and established friction values. The glass specimens were corrosion-resistant microscope slides. The steel specimens were made from SAE 1020 stock. Hexadecane was purified of polar compounds by percolation through silica gel and fuller's earth consecutively. Cuprous oxide $Cu_2O$ and cupric oxide $CuO$ were obtained commercially as chemically pure powders.

Specimen preparation. - The copper specimens were made small to permit them to be set in the diffraction adapter of the RCA type-B electron microscope. The flat specimens were machined to 3/32 by 1/8 by 3/16 inch and the convex specimens were bullet-shaped, cut out of 1/8-inch rod, and tipped with a 1/4-inch radius. After machining, the specimens were annealed by heating to $1200^{\circ}$ F and were quenched and simultaneously descaled by immersion in 20-percent alcohol.

The proper cleaning of the copper specimens was very important for reproducibility and to obtain initial high values of $\mu$. Details of this procedure and the results obtained as well as the procedures for steel and glass specimens are given in the appendix.

The standard surface finish was created by abrasion with 2/0 emery paper followed by a short electrolytic etch. The final surface finish consisted of smooth hills and valleys with a roughness of about 5 microinches root mean square.

Oxide films were formed on copper by heating clean specimens in air under different time-temperature combinations. Films of $Cu_2O$ (500-1000 A thick as determined by interference colors) were formed by heating copper 100 minutes at 150° C. Films of CuO with a thickness greater than 1500 A (several orders of interference colors to gray-black) were formed by heating copper 5 minutes at 390° to 400° C. The composition of the films and the specimen cleanliness were confirmed by electron diffraction.

Compacts of oxide powders were made by pressing and sintering chemically pure $Cu_2O$ and CuO powders. Details of the process are given in the appendix.

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Experimental procedure. - For all sets of specimens, the procedure was the same and the run was repeated with new specimens three or more times. The freshly cleaned specimens were mounted without delay in the specimen holders of the apparatus and the load applied. The cover was put in place and dry air was started flowing through the enclosure. When the relative humidity of the escaping air had dropped to 10 percent, the reciprocating action was started. In the case of glass specimens, microscopic observations during fretting were correlated with the friction tracing.

Fretting runs in the presence of hexadecane were made by applying to the contact area, with a glass rod, a drop of hexadecane taken fresh from the end of the percolating column. Surface tension held the liquid around the contact area.

The normal load was measured at the end of each fretting run by pulling upward on the flat specimen, (by means of weights, pan, pulley, and cord assembly) with just enough force to separate the specimens.

Coefficient of friction (ratio of friction force to measured normal load) was plotted against the number of fretting cycles for each run. The length of most runs was 300 cycles, which was enough for the friction coefficient $\mu$ to reach an essentially constant value. For unidirectional sliding experiments, the procedure was the same except that the run was limited to one sliding pass of approximately 1/4 inch.

Chemical spot tests were used for identification of small quantities of debris. Details of the procedure are given in the appendix. Electron diffraction was used to determine the chemical composition of surfaces before the runs and also to identify debris when possible.

## RESULTS

Preliminary experiments showed that the values of $\mu$ and the extent of damage are influenced by several factors. The coefficient of friction for any given run drops 0.05 when the relative humidity is increased from between 5 and 10 percent to between 30 and 50 percent, and it recovers when the drier air is readmitted. Specimens of copper ranging in hardness from Rockwell F-40 to F-90 were fretted together. The fact that the friction curves were almost the same over the whole hardness range indicated that, within those limits, hardness had little effect on the value of $\mu$. Greater total damage was, however, observed with the softer copper than with the hard. Increasing the amplitude or load also increased fretting damage.

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The following conditions were selected and held constant throughout all runs: humidity, 5 to 10 percent; amplitude, 0.006 inch; frequency, 5 cycles per minute; load, approximately 175 grams; copper hardness, Rockwell F-40; and surface finish, abraded on 2/0 emery paper and etched.

Fretting of copper against glass. - Fretting experiments were conducted with copper against glass under the standard conditions. Correlation of the microscopically observed action and the coefficient of friction for a typical run is given in the following table:

| Number of cycles | Action observed | Coefficient of friction, $\mu$ |
|---|---|---|
| 0-1/2 | Shearing off of copper peaks to produce plateaus and loose copper particles. Some material adheres to and is transferred to glass in form of streaks. | 1.2 |
| 1/2-1 | Rapid increase in size of plateaus. More loose copper particles and streaks on glass. | 1.3 |
| 2-6 | Further increase in size of plateaus. More loose copper particles and broad streaks on glass. | 1.6 |
| 6-10 | Transfer of material to glass as discontinuous film which appears greenish by incident illumination. | 1.2-1.0 |
| 10-20 | Increase in amount of film on glass to cover contact area. Distinct plowing of copper specimen by concentrations of material adhering to glass. | 1.0-0.8 |
| 20-50 | Plowing action predominates, with occasional changes in geometry as result of wiping off of parts of film. | 0.8-0.6 |
| 50-100 | Plowing action subsides and copper specimen contact area becomes encrusted with oxide. | 0.6 |
| 100-300 | Constant coefficient of friction state, in which sliding occurs between material adhering to glass and oxide crust on copper. Oxide debris pushed out of contact area. (Identified later as CuO.) Wear spot slowly increases in diameter. | 0.6-0.5 |

The friction curve obtained by averaging the curves from individual runs is given in figure 2. The coefficient of friction $\mu$ was initially 1.2, increased to 1.6, and then decreased to a value near 0.6. The physical action was the same as that observed at frequencies of 120 cycles per second for glass against steel (ref. 1), where stain appeared on the glass and ferric oxide was subsequently formed and extruded from the contact area. The results reported herein confirm the conclusion of reference 1 that fretting starts with the first half cycle of vibration.

<u>Fretting of copper against copper</u>. - Copper was fretted against copper in runs lasting 1/2, 5, 50, and 100 cycles as well as the usual 300 cycles, using new specimens for each run. The damage to the contact area was observed after each run and correlated with $\mu$ values. These results are presented in the following table: 2929

| Number of cycles | Observations | Coefficient of friction, $\mu$ |
|---|---|---|
| 1/2 | Sliding tracks formed by protruding "welded" fragments on both specimens. Some loose Cu particles were present. | 1.2 |
| 5 | Sliding tracks became distinct furrows. | 1.3 |
| 50 | Furrows increased in number and breadth. Bottoms of furrows appear smooth and Cu colored. Plowed out debris collects at ends of furrows. | 0.8-0.9 |
| 100 | Furrows merge into one large shallow elliptical concavity. For first time, debris contains visible amounts of dark oxide. | 0.55-0.6 |
| 300 | Proportion of oxide in debris has increased, and can be identified as CuO. | 0.55-0.6 |

The friction curve for copper against copper is presented in figure 3, where all the data obtained for 12 similar fretting runs are plotted. The data points can be enveloped as shown by dotted lines, and the vertical distance represents the spread in $\mu$ values obtained. The average friction curve of copper against copper is represented by the solid line drawn within the envelope. Each of the 12 runs, when plotted separately, showed a shape similar to this average curve.

The initial $\mu$ values obtained (fig. 3) were approximately the same as those obtained during unidirectional sliding of copper against copper under the same conditions (see table I) and for metals sliding over similar metals (ref. 3, pp. 80-81). This similarity indicates that the contact between specimens was essentially metal-to-metal during the first few cycles of fretting, and that the first damage was a result of adhesion and metal transfer. No doubt some oxide was present as ruptured films. The rise in $\mu$ during the first five cycles was apparently caused by an increase in the amount of metal-to-metal contact, as adsorbed gases and thin oxide films ($Cu_2O$, < 100 A thick (ref. 3, p. 149) unavoidably formed at room temperature) are ruptured and scrubbed off.

2929 After the initial high values of $\mu$, a reduction in $\mu$ from 1.3 to approximately 0.55 was observed, associated with plowing and an increasing concentration of debris in and around the contact area.

A photomicrograph of a 15 to 1 taper section of the damaged area on copper after fretting against copper for 300 cycles is shown in figure 4. The presence of imbedded oxides and the severe deformation of bulk metal below the surface are evident. The damage shown is very similar to that presented in reference 4, which was produced by repeated nonreciprocating sliding passes over the same track. This indicates that, for copper, similar damage results from fretting and from sliding.

Fretting runs with copper against copper in the presence of hexadecane were made to measure $\mu$ and determine damage with reduced oxygen availability. The friction curve is similar to that of copper against copper in air except that the peak and constant $\mu$ values are higher (fig. 5). For copper against copper in hexadecane the initial $\mu$ is 1.2, the peak $\mu$ is above 1.6, and the constant $\mu$ is approximately 0.7. The contact area was damaged by excessive galling. The transferred and welded copper particles were larger and more extensive, and the pits were deeper, than for copper against copper in air. No loose copper or oxide particles were observed microscopically. For hexadecane, the final constant value of $\mu$ was approximately 0.15 higher than for air and occurred approximately 50 cycles later.

<u>Fretting of copper oxide compacts against copper oxide compacts</u>. - Fretting runs were made with CuO compacts against CuO compacts and $Cu_2O$ compacts against $Cu_2O$ compacts to determine the friction curve and the type of damage without any possible metal-to-metal contact. The friction curves are shown in figure 6, with that of copper against copper for comparison. The value of $\mu$ for CuO compacts against CuO compacts started at 0.75 and reduced to 0.6. Simple abraded spots were formed on the specimens, and the debris was identified as CuO. The value of $\mu$ for $Cu_2O$ compacts against $Cu_2O$ compacts started at 0.6 and reduced to a constant value of 0.5. Again simple abraded spots were formed on the specimens, but they were partly encrusted with an unidentified yellow-green stain. The loose debris ($Cu_2O$) was also yellow-green. Figure 6 shows that constant values of $\mu$ for both oxide compacts are similar to the constant value of $\mu$ for copper against copper. These results suggest

that the constant $\mu$ value of copper against copper is a result of the reciprocating sliding of copper oxide on copper oxide. The oxide in the debris resulting from fretting of copper against copper was identified by spot tests and electron diffraction as CuO. Although the constant $\mu$ for copper against copper appears to lie closer to that of $Cu_2O$ than that of CuO, the difference among all three curves is within the spread normally obtained in friction studies.

Fretting of copper oxide films (on copper) against copper oxide films (on copper). - Fretting runs were conducted with $Cu_2O$ film (on copper) against $Cu_2O$ film (on copper) and CuO film (on copper) against CuO film (on copper) to determine the influence of relatively thick oxide films on the coefficient of friction and nature of damage during the start of fretting. The friction curves are shown in figure 7. Both curves show the same trend as the curve of copper against copper, which is included for comparison. The presence of the $Cu_2O$ film results in a lower initial value of $\mu$ (1.0) than is the case with copper against copper (1.2), and the peak is lowered from 1.3 to 1.1. The results show, however, no essential difference in the constant values of $\mu$ for copper against copper whether a 500 to 1000 A film or a 50 to 100 A film (present on copper against copper, fig. 3) of $Cu_2O$ is present initially. 2929

The presence of CuO film causes a greater initial lowering of $\mu$ (to 0.8 from 1.2 for copper), and the peak is lowered to 0.88. Again the constant values of $\mu$ are approximately the same as those of copper against copper.

The results indicate that $Cu_2O$ and CuO films on copper (which flows plastically at light loads) reduce the value of $\mu$ initially and are observed to quickly rupture. The films do not reduce the damage to the contact area and after 100 cycles have little influence on the progress of fretting.

Fretting of copper against steel. - Fretting runs were made with copper against steel to determine whether metal transfer occurs during fretting of dissimilar metals as it does during pure sliding. The friction curve is shown in figure 8. The initial value of $\mu$, 0.8, reduces to an essentially constant $\mu$ of approximately 0.5. The constant $\mu$ value is near the constant value of copper against copper. Adhesion and transfer of copper to the steel occurred immediately, causing a gouge in the copper and a copper-colored built-up area on the steel. Fretting debris characteristic of copper against copper was present. This experiment indicates that, in the start of fretting of copper against steel, as for the case of copper against glass, transfer of copper occurs and the ensuing action may be essentially that of copper against copper. A similar result has been obtained in unidirectional sliding of platinum on silver (ref. 3, pp. 80-81), where transfer of silver occurred after a short distance of sliding, and the friction became characteristic of silver on silver.

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## DISCUSSION

The results indicate that during the first few cycles of fretting of copper against copper (with thin or thick oxide film), copper against glass, or copper against steel, adhesion and metal transfer occurred as it does in unidirectional sliding. The accompanying coefficients of friction were high, being approximately equal to values obtained in unidirectional sliding. After approximately 100 cycles of fretting, oxide debris appeared in and around the contact area and the coefficient of friction had reduced to a constant value approximately the same as the value obtained in sliding compacts of copper oxide against compacts of copper oxide.

Table I compares $\mu$ values obtained during fretting with values obtained for unidirectional sliding under the same conditions and values obtained by other investigators.

The reduction in the value of $\mu$ between the initial and constant values observed during the fretting of copper against glass, copper, and steel could be caused by: (1) an increase in the concentration of lower-shear-strength copper oxides in and on the rubbing surfaces; (2) the presence of loose granular particles in the contact area, as evidenced by the decrease in $\mu$ obtained during the fretting of the oxide compacts; and (3) a decrease in plowing.

## SUMMARY OF RESULTS AND CONCLUSIONS

Experiments were conducted to determine the coefficient of friction and damage during initial stages of fretting of copper. The following results lead to the conclusion that fretting of copper starts with the same mechanical damage that occurs during unidirectional sliding:

The fretting of glass, copper, or steel against copper starts with adhesion and metal transfer (galling) associated with a high coefficient of kinetic friction $\mu$ ($>1.0$) and damage approximately the same as that obtained during unidirectional sliding between similar metals. After the initial high values of $\mu$, a reduction in $\mu$ was observed, associated with reduced plowing and increasing concentration of debris in and around the contact area. After approximately 100 cycles of fretting, the coefficient of friction reached a constant value (0.5-0.6) approximately the same as that obtained with either cuprous or cupric oxide compacts.

The presence of preformed cuprous or cupric oxide films on copper did not prevent the occurrence of fretting but only lowered the initial coefficient of friction.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, July 14, 1953

## APPENDIX - SPECIAL TECHNIQUES

Cleaning of copper specimens. - A preliminary investigation was conducted on the effect of various cleaning methods on the values of $\mu$ of copper against copper during the first few fretting cycles. The results are presented in table II, along with the information obtained from reflection electron-diffraction patterns. Surface cleanliness was a prerequisite for high initial $\mu$ values, as well as for reproducibility in $\mu$. The most effective cleaning procedure (given at bottom of table II) was as follows: 2929

(1) Lightly abrade in air on 2/0 emery paper.

(2) Scrub very thoroughly with clean cotton or fine wire brush[1] under redistilled benzene to remove adhering emery.

(3) Wash specimen with strong stream of redistilled benzene and dry thoroughly.

(4) Etch electrolytically in solution composed of 5 milliliters glacial acetic acid, 10 milliliters nitric acid, and 30 milliliters water with current from a 3-volt dry battery giving a current density of 0.5 amperes per square inch. The etching time will depend upon the size of the specimens and, in these experiments, was about 2 seconds or until greenish streamers dropped away from the specimen.

(5) Remove specimen and very quickly wash in water.

(6) Dry in vacuum or by room temperature air from a blower. When cleaned, the copper appeared pink and oxide-free, but by the time the specimen was mounted in the apparatus, and low humidity achieved, a film of $Cu_2O$ 50 to 100 A thick had formed. The presence of this film which formed in air at room temperature was discussed in the analysis of the experimental results.

The ease with which emery became imbedded in the copper during abrasion was noted. Much time and care was used in removal of the emery.

Cleaning of steel specimens. - The procedure for cleaning the steel specimens was as follows:

(1) Abrade on 2/0 emery paper.

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[1]A small brush made of 0.002 in. platinum-iridium wire in a stainless-steel handle was found very useful because it could be heated to redness repeatedly to remove traces of grease.

(2) Immerse 10 minutes in a 20-percent solution of hydrochloric acid in anhydrous methyl alcohol.

(3) While immersed, scrub thoroughly with fine wire brush to remove dark film.

(4) Rinse and scrub in fresh anhydrous methyl alcohol.

(5) Rinse in anhydrous methyl alcohol.

(6) Dry with blower.



Certain precautions were necessary during cleaning. The benzene, alcohol, and water used were freshly redistilled. All vessels used were of pyrex and were cleaned in fresh sulfuric acid - sodium dichromate cleaning solution, followed by washing in redistilled water and oven drying. All specimen and vessel handling tools were cleaned by heating to redness. The working area was maintained grease-free. The application of heat (such as from hot tongs) was avoided to prevent unwanted oxidation.



These procedures gave greater freedom from grease, as revealed by the very high initial $\mu$, and from excessive oxides, as shown by electron-diffraction examination.

Compacting of copper oxide powders. - The $Cu_2O$ specimens were shaped out of a compact made by pressing dry powder at 60,000 pounds per square inch and sintering in vacuum at $1600^\circ$ F for 7 hours. The CuO specimens were shaped out of a compact made by pressing at 20,000 pounds per square inch and sintering at $1775^\circ$ F for 6 hours. The compacts were cooled in the furnaces to $700^\circ$ F to minimize cracking. X-ray and electron diffraction revealed that the process did not change the composition of the material. The specimens were mounted in an alloy that melts at $200^\circ$ F, cleaned by light abrasion with 2/0 emery paper followed by a thorough wash in redistilled alcohol, and dried.

Chemical spot tests. - The spot tests were conducted on white and on black porcelain spot plates, illuminated by a cool light, and sometimes observed with a low-power stereo microscope. In case of debris on the glass specimens, examination was made on the glass. The insolubility of a particle in dilute hydrochloric acid indicated the presence of copper. If the particle dissolved in 5-percent hydrochloric acid and addition of a crystal of potassium iodide formed a yellow solution, cupric ion or CuO was indicated. This was confirmed by addition of a drop of starch solution, which was immediately colored purple. Blanks of distilled water were always run, because in the case of addition of potassium iodide, some of the iodide will be oxidized to iodine and will thus form a yellow solution simply on standing in air. However, the rate of formation was much slower than when CuO was present.

If the particle dissolved in 5-percent hydrochloric acid and addition of a crystal of potassium thiocyanate formed a white precipitate, the presence of cuprous ion or $Cu_2O$ was indicated.

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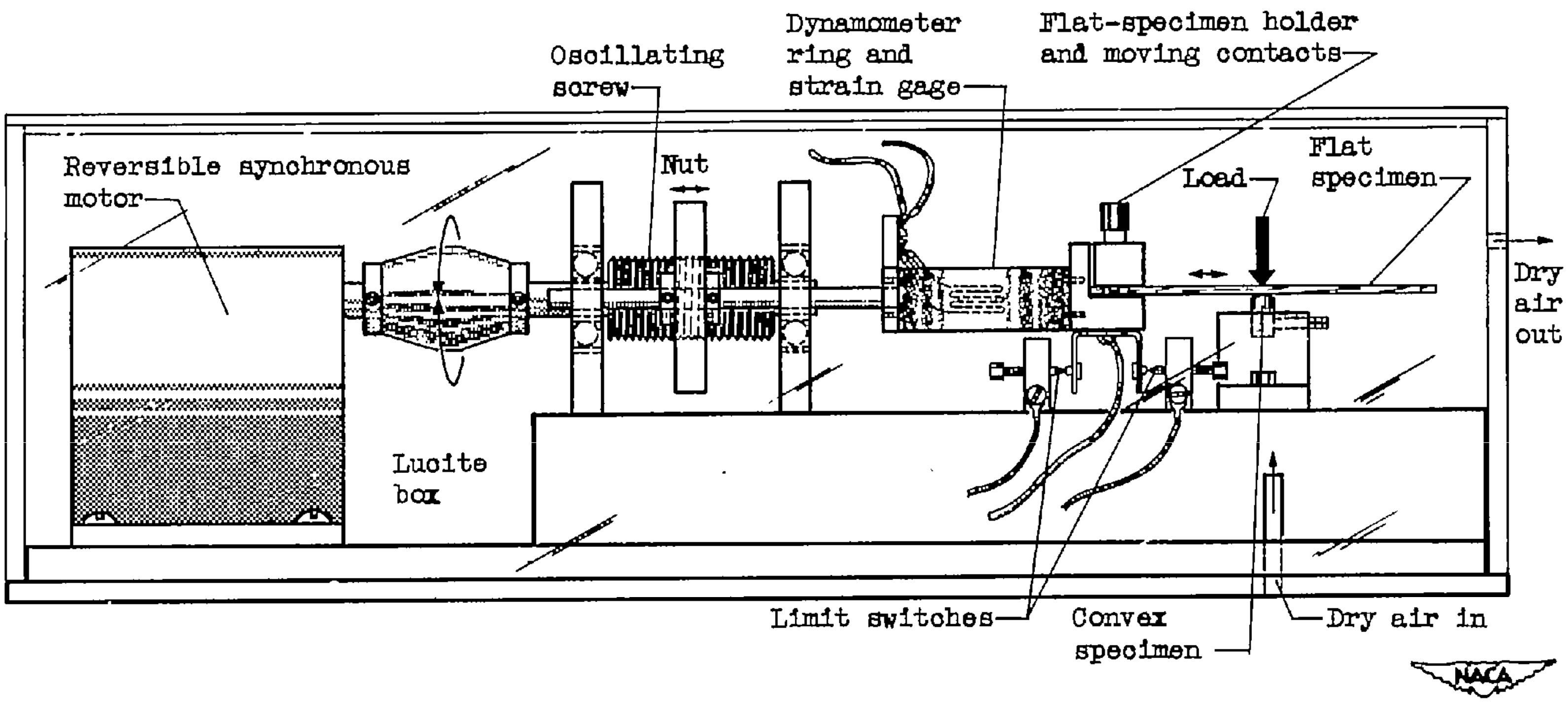
TABLE I. - COMPARISON OF COEFFICIENTS OF FRICTION μ OBTAINED DURING FRETTING AND DURING SLIDING

| Material combination | Fretting | | | Unidirectional sliding μ (approx.) | |
|---|---|---|---|---|---|
| | Approximate μ | | | Under conditions similar to fretting | Measurements by other investigators |
| | Initial | Peak | Constant (range) | | |
| Cu vs. Cu | 1.2 | 1.3 | 0.55 | 1.4-1.7 | 1.0 - 1.5 Bowden (ref. 3, p. 80)<br>1.2 - 1.3 Wilson (ref. 5)<br>1.8 Whitehead (ref. 6, p. 114) |
| Cu vs. glass | 1.2 | 1.6 | 0.6 | ------- | ---------------------------------- |
| Cu vs. steel | 0.8 | No peak | 0.5 | ------- | 0.9 Bowden (ref. 3, p. 79) |
| $Cu_2O$ film vs. $Cu_2O$ film | --- | --- | --- | ------- | 0.4 - 0.5 Whitehead (ref. 6, p. 114) Unruptured at light load |
| $Cu_2O$ film vs. $Cu_2O$ film (ruptured) | 1.0 | 1.2 | 0.5 | 0.8-1.2 | 1.2 - 1.3 Whitehead (ref. 6, p. 114) Ruptured at heavier loads |
| CuO film vs. CuO film | --- | --- | --- | 0.5-0.7 | ---------------------------------- |
| CuO film vs. CuO film (ruptured) | 0.8 | 0.9 | 0.5-0.6 | 0.8-0.9 | ---------------------------------- |
| $Cu_2O$ compact vs. $Cu_2O$ compact | 0.6 | No peak | 0.5 | 0.6-0.7 | ---------------------------------- |
| CuO compact vs. CuO compact | 0.7 | No peak | 0.6 | 0.7 | ---------------------------------- |

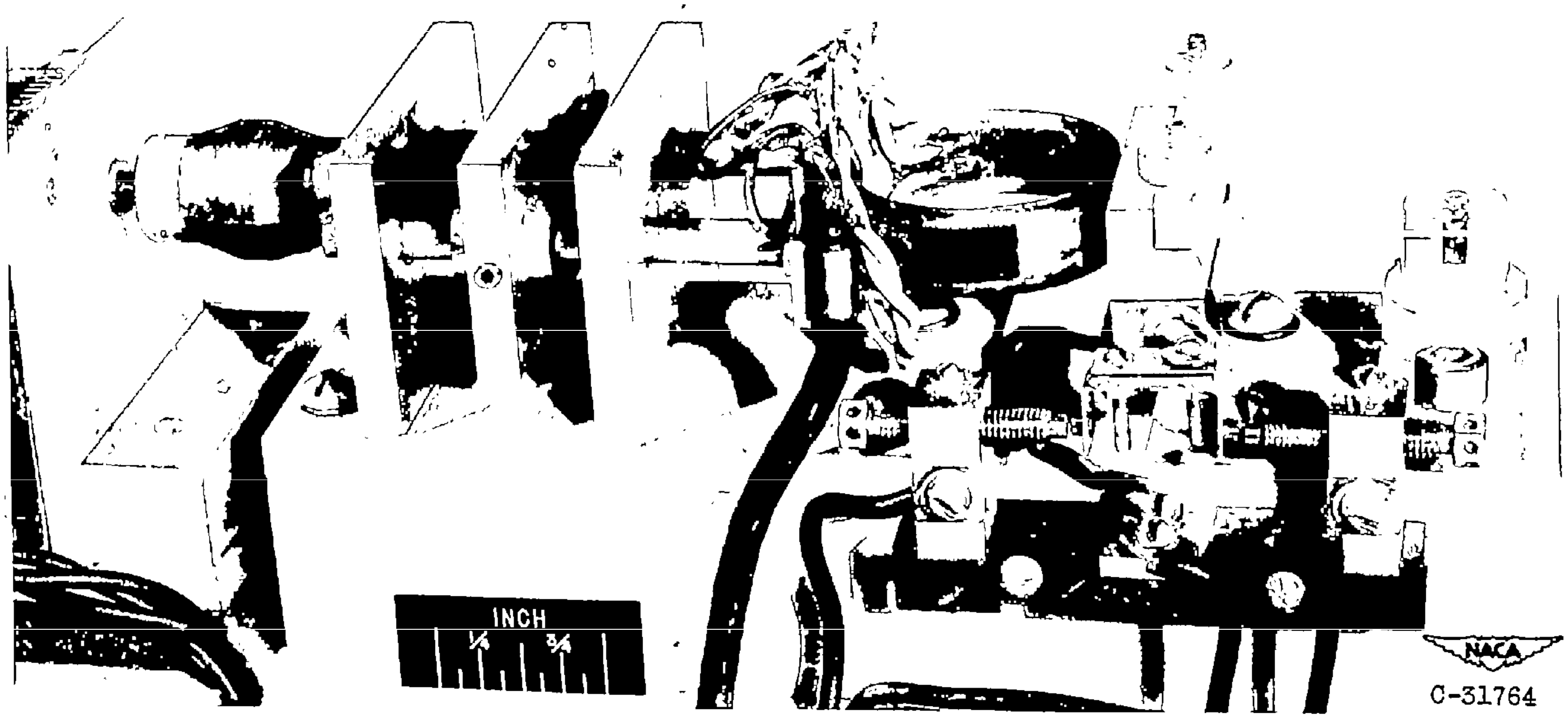
TABLE II. - SURFACE COMPOSITION AND COEFFICIENT OF FRICTION RESULTING FROM VARIOUS CLEANING PROCEDURES FOR COPPER

| Procedure | Composition of surface (by electron diffraction) | Initial coefficient of friction |
|---|---|---|
| Abraded on 2/0 emery paper in air | Cu and $Cu_2O$ | 0.40 |
| Abraded on 2/0 emery paper under benzene | Cu and trace $Cu_2O$ | .41 |
| Abraded on 2/0 emery paper and washed in alcohol | Cu and trace $Cu_2O$ | .56 |
| Abraded on 2/0 emery paper under benzene and washed in alcohol | Cu and trace $Cu_2O$ | .65 |
| Scrubbed in paste of alumina and alcohol, and washed in alcohol | Unknown and alumina | .99 |
| Abraded on 2/0 emery paper under benzene, scrubbed in paste of alumina and alcohol, and washed in alcohol | Cu and trace oxide and alumina | 1.01 |
| Abraded on 2/0 emery paper under benzene, scrubbed in paste of alumina and water, and washed in water | Unknown and trace alumina | 1.03 |
| Abraded on 2/0 emery paper in air, washed in benzene, dried, electrolytically etched, washed in water, and dried | Cu plus very slight trace $Cu_2O$ | 1.21 |




(a) Diagram.

Figure 1. - Fretting apparatus.




(b) Photograph.

Figure 1. - Concluded. Fretting apparatus.

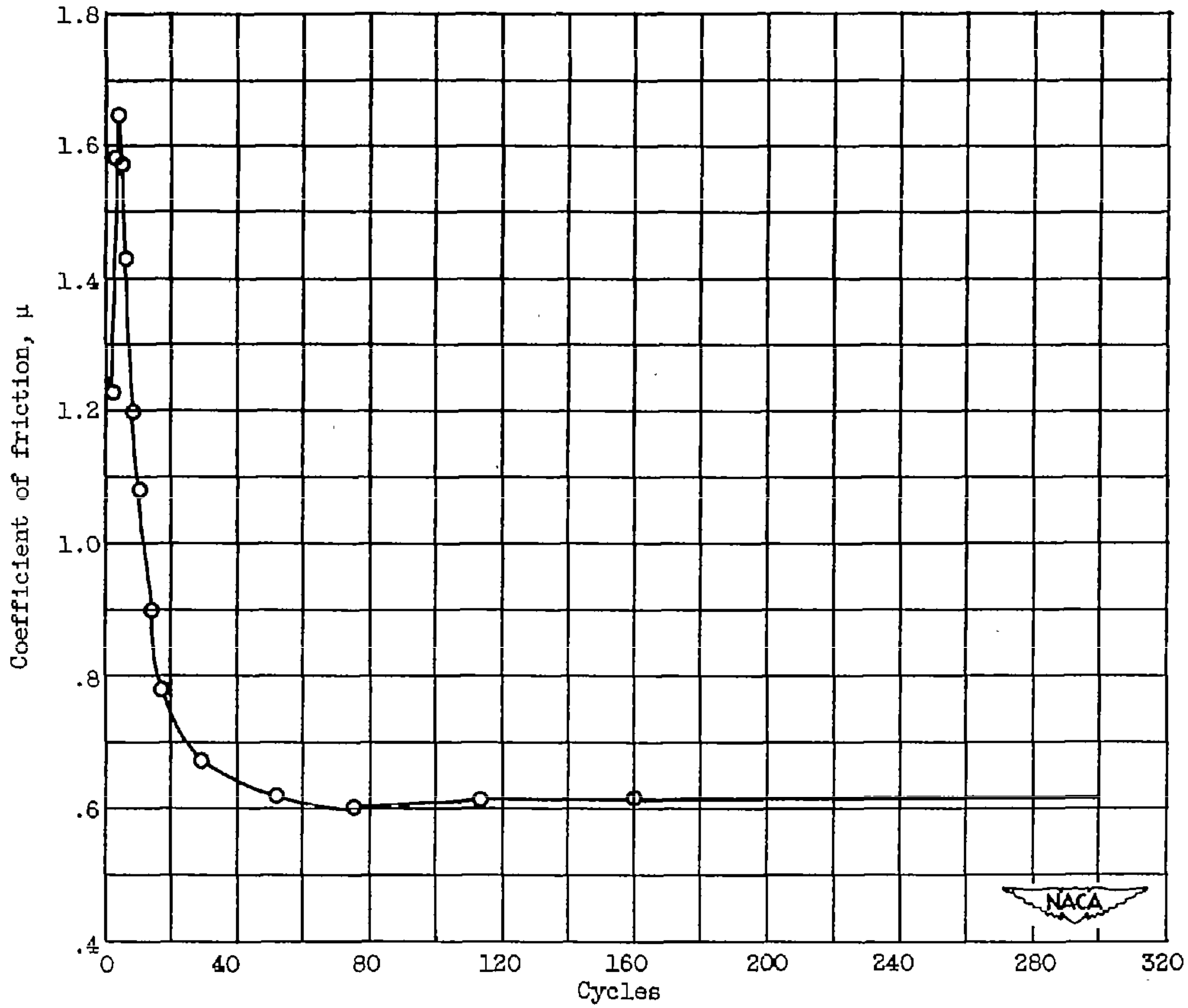



Figure 2. - Friction during fretting of copper against glass.

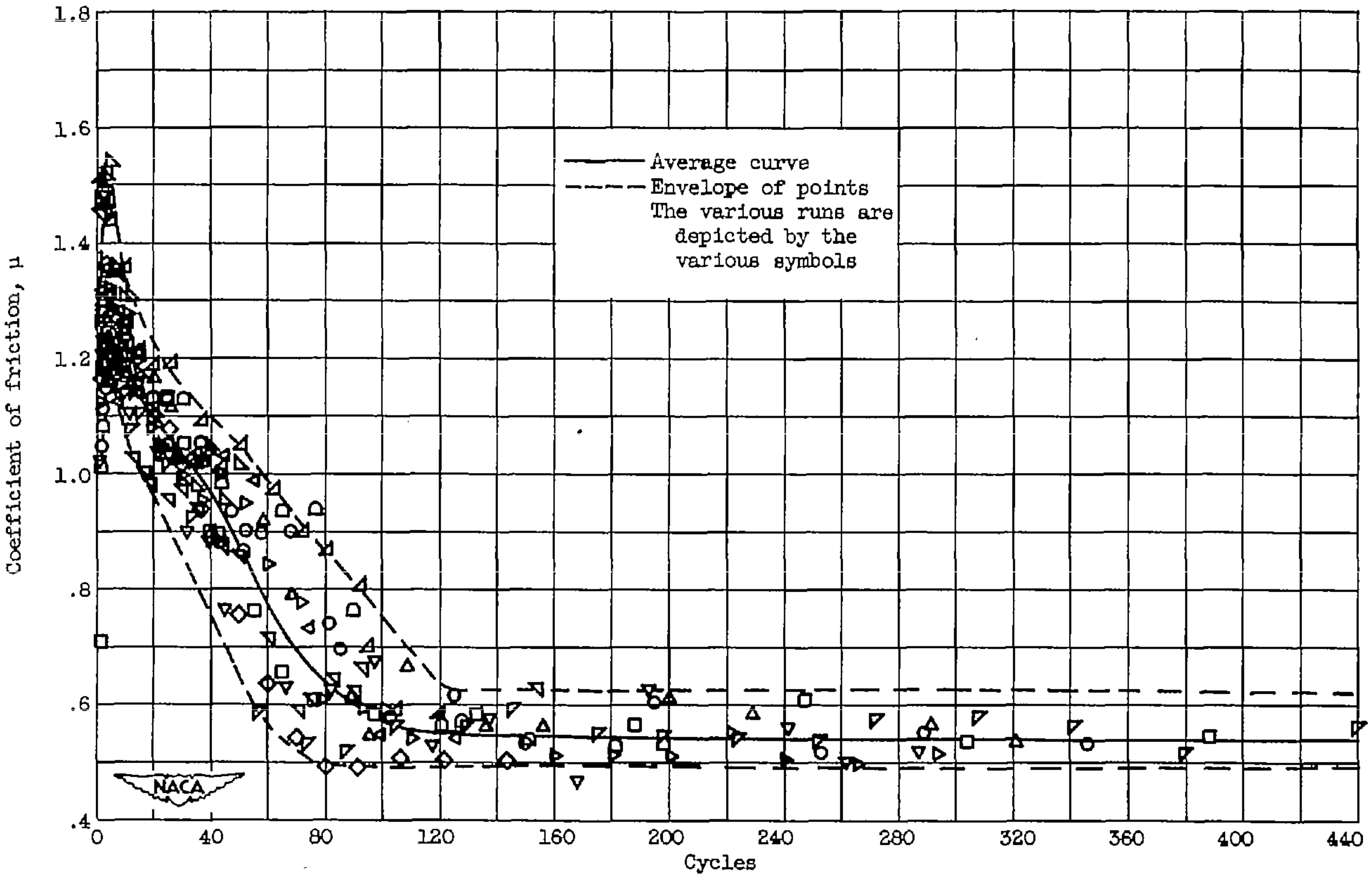



Figure 3. - Friction during fretting of copper against copper showing data for 12 similar runs.

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CG-3 back

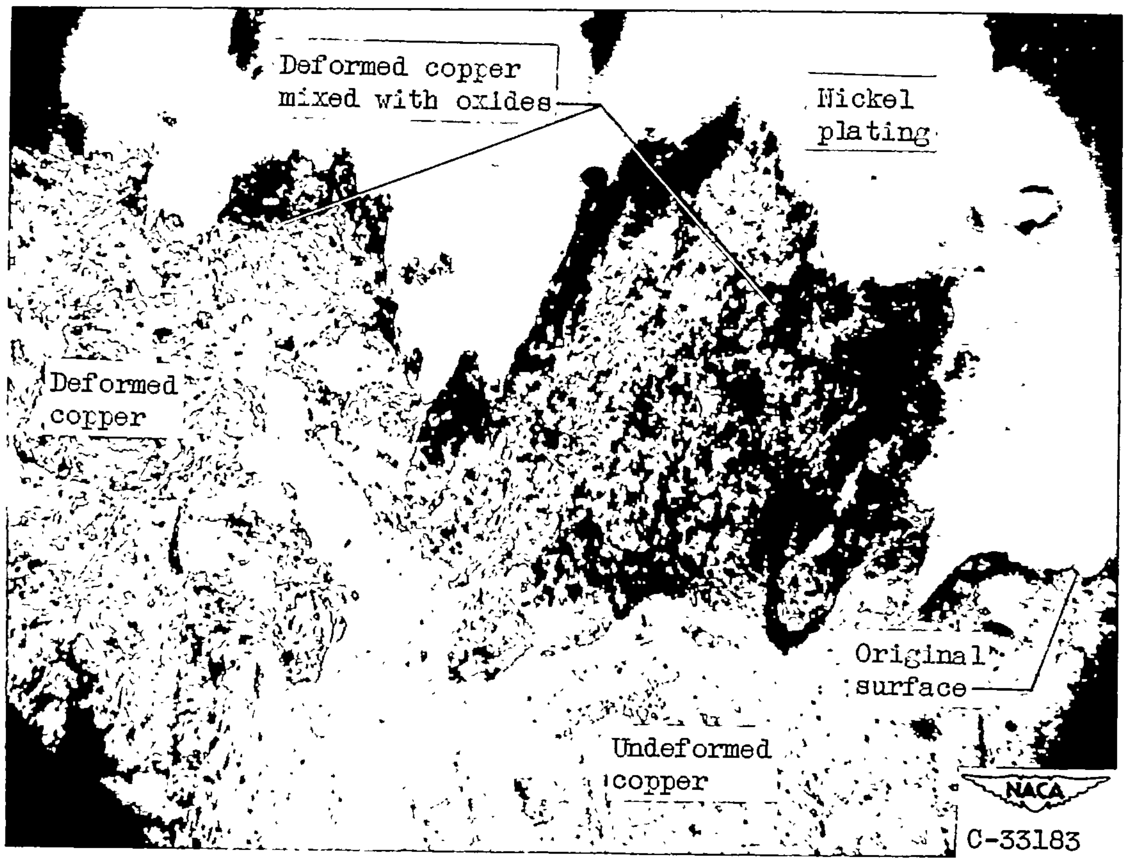


Figure 4. - Photomicrograph of taper section of fretted area of copper specimen fretted against copper for 330 cycles. Horizontal magnification, X500; vertical magnification, approximately X7500.

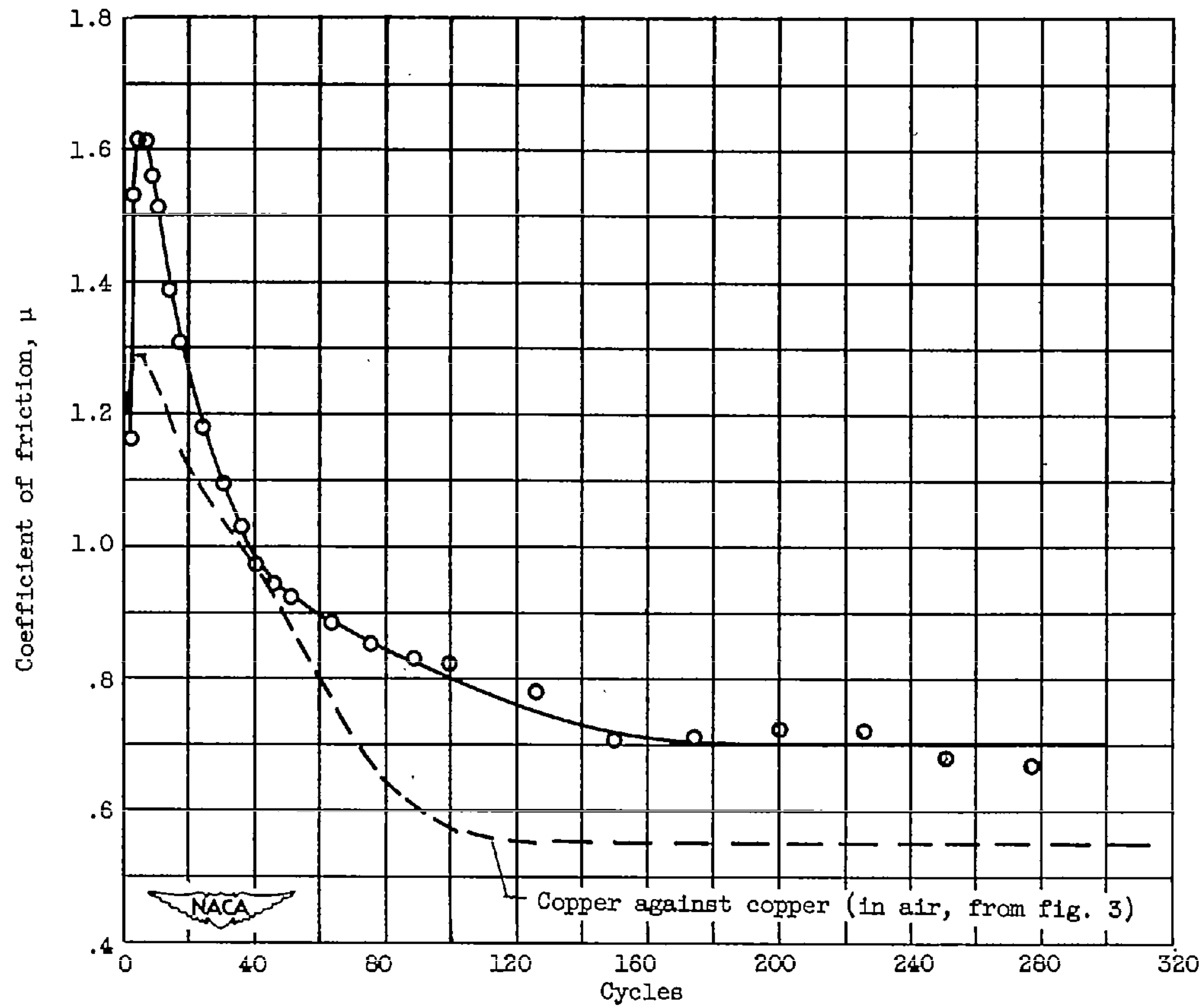


Figure 5. - Friction during fretting of copper against copper in hexadecane.

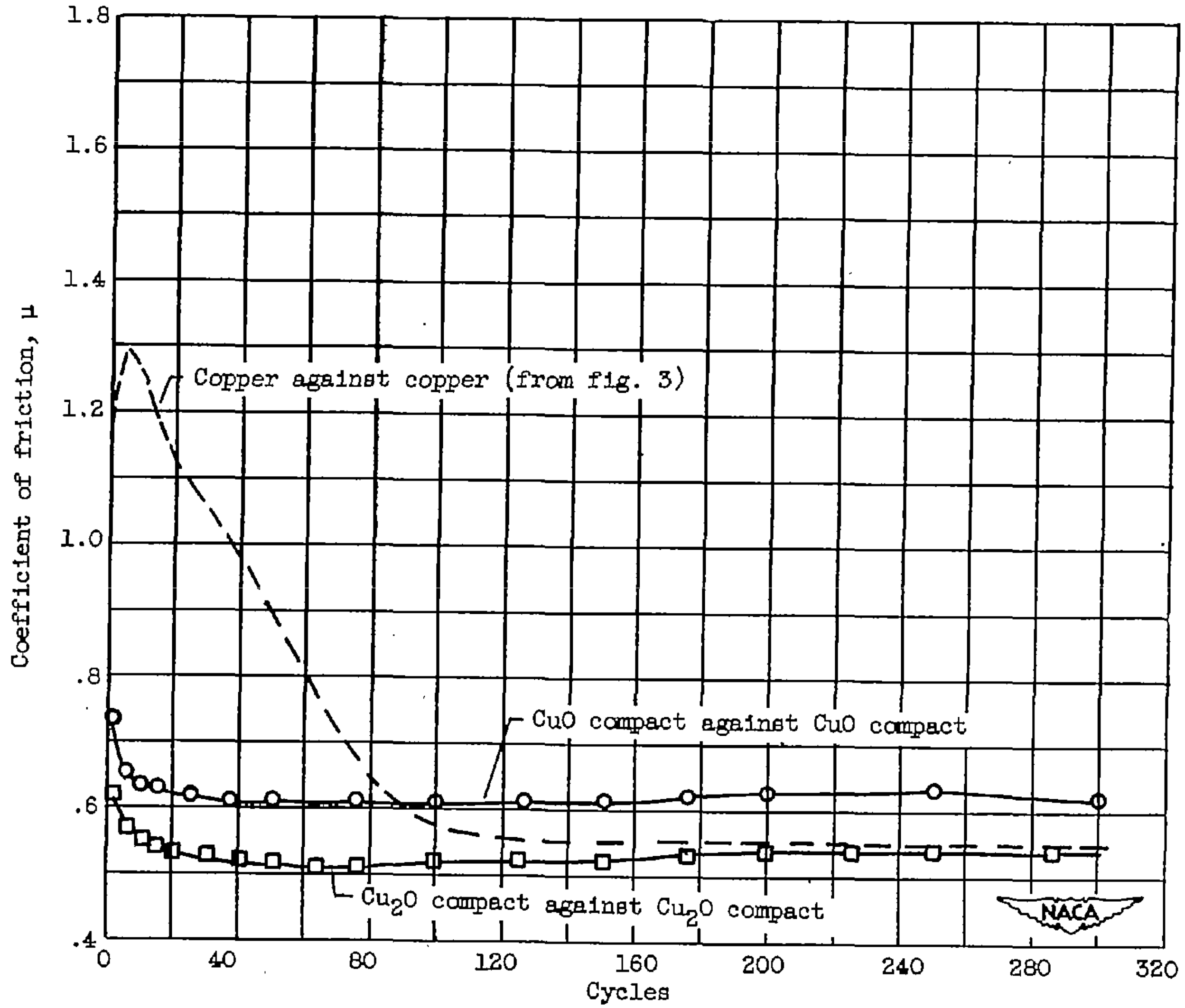


Figure 6. - Friction during fretting of copper oxide compacts.

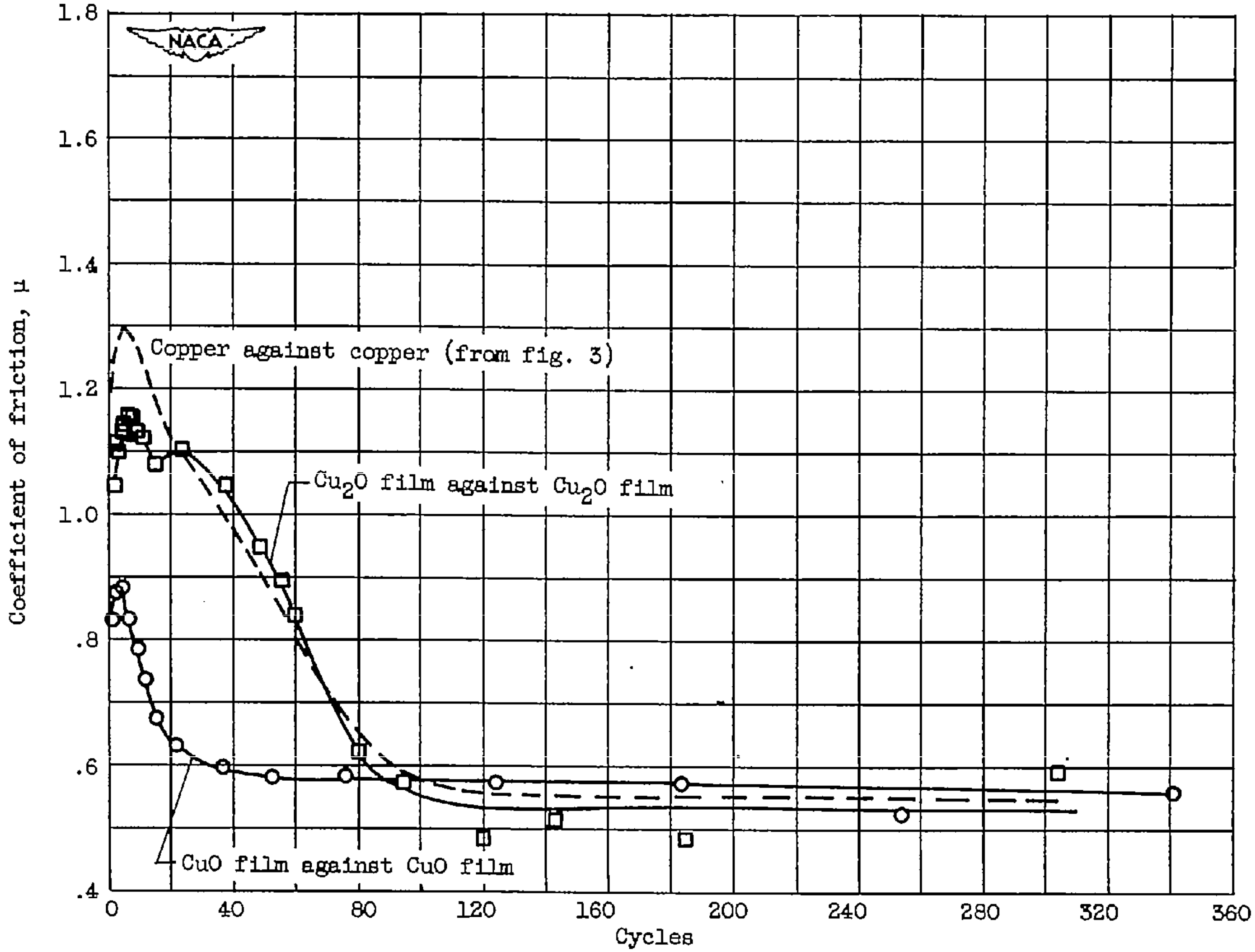


Figure 7. - Friction during fretting of copper oxide films.

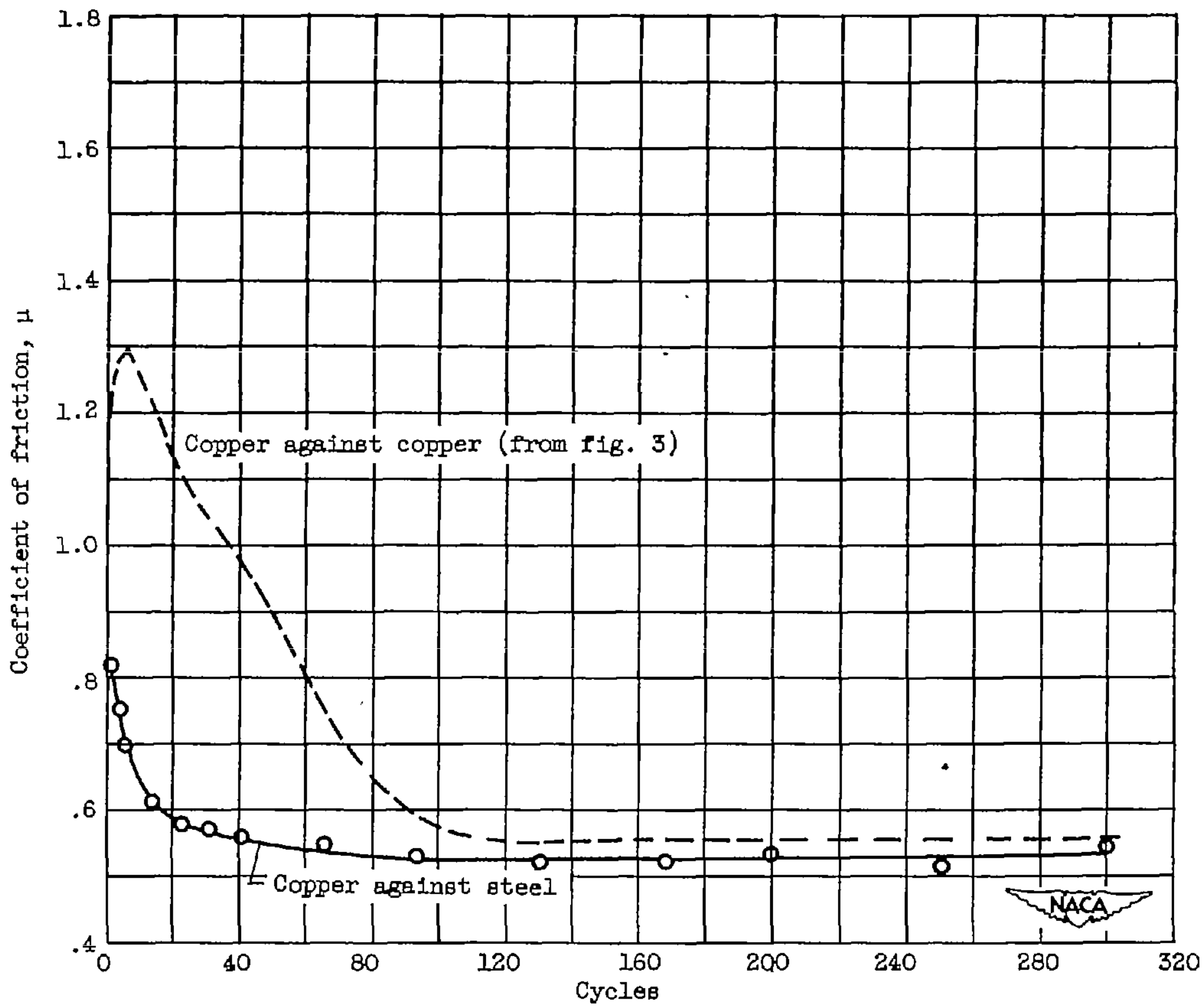


Figure 8. - Friction during fretting of copper against steel.



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